

AIRS Observations of Deep Convective Clouds¹

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Abstract

Large thunderstorms can be identified in the AIRS data as areas where the brightness temperature of the 1231 cm^{-1} atmospheric window channel in non-polar areas is less than 210 K. Each day about 6000 large thunderstorms are identified, almost exclusively within 30 degrees of the equator. Since the size of the AIRS footprint at nadir is 13.5 km, a brightness temperature of less than 210 K indicates that the top of the anvil of the thunderstorm protrudes well into the tropopause. Such objects are commonly referred to as Deep Convective Clouds (DCC). Our interest in DCC was motivated by the question "Are severe weather events increasing due to global warming". Each DCC is a severe weather event, although not on the scale of the much less frequent hurricanes, which can be identified in the AIRS data as clusters of several hundred DCC. The number of DCC per day has been fairly stable over the past four years for the mean of the tropical oceans, but a significant increase can be seen day and night in the Atlantic Ocean. The number of DCC per day shows a strong seasonal and latitudinal dependence, with the peak count lagging the solstice of the latitude zone by about 2 months. The most prominent features in brightness temperature spectra of DCC are due to stratospheric CO_2 , Ozone and Methane. In the channels with weighting functions below the stratosphere the brightness temperature is typically 205 K, with a characteristic 1 to 2.5 K drop between 1000 and 750 cm^{-1} , equivalent to a 2-4 % drop in emissivity. This is likely due to the presence of cirrus (ice) particles. Some of this analysis of DCC can be extended using past and future operational sounders in polar orbit.

AIRS is an imaging hyperspectral grating-array spectrometer on the EOS Aqua spacecraft, launched on May 4, 2002.

Keywords: infrared hyperspectral temperature sounding climate hurricane EOS Aqua

1. Introduction

The number of hurricanes which have made landfall on the East Coast of the US between 1900 and 1997 (Bove et al. 1998) has averaged 1.6 per year with standard deviation of 1.3, with a range from zero to 6. A hurricane count of 6 per year constitutes a 3 sigma event, which is not unreasonable in the count from 97 years. The question: are severe weather events increasing due to global warming can not be answered reliably from the analysis of the frequency of very infrequent events, such as hurricane counts. Even using all hurricanes reported globally, about 100 per year with a standard deviation of 10, does not produce a

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high enough count for reliable statements of trends or shifts in the geographic distribution. We have therefore used AIRS data to find events which are severe enough to be potentially correlated with hurricanes, but are much more frequent. AIRS (Aumann et al. 2003) is an imaging hyperspectral grating-array spectrometer on the EOS Aqua spacecraft. It was launched on May 4, 2002 in a polar orbit with 1:30 pm ascending node and has returned, essentially uninterrupted, 3 million spectra of the radiance upwelling since September 2002. AIRS scans ± 49 degrees cross-track and covers the entire globe essentially twice each day.

The events seen in the AIRS data with reasonably high frequency are very large thunderstorms, usually referred to as Deep Convective Clouds (DCC). We define DCC as spectra where the brightness temperature in the 13.5 km nadir AIRS footprint in the 1231 cm^{-1} atmospheric window channel is less than 210 K at ± 60 degree latitude. The 210 K threshold is somewhat arbitrary. Each DCC is a severe weather event, although not on the scale of the much less frequent hurricanes, which can be identified in the AIRS data as clusters of several hundred DCC. In the following we will discuss the spatial distribution, the frequency, seasonal frequency dependence and spectral appearance of these DCC, as seen in the AIRS data.

The results presented in the following are based on the analysis of data collected in the AIRS Climate Data Subset (ACDS). Each day the data from AIRS are converted into 60 Gbytes of calibrated radiances. Filtered from these data and saved in the ACDS (sometimes referred to as AIRS Calibration data subset or AIRS Clear data subset) as one 300 Mbyte file per day are spectra which are identified as cloud-free, are from the overpass over selected ground calibration sites (such as Dome Concordia), spectra from DCC and 9 spectra in a 3x3 pattern ("golfball") randomly selected approximately every 1500 km along the nadir track. The ACDS files are available via ftp from the GSFC DAAC.

2. Results

2.1. Count statistics

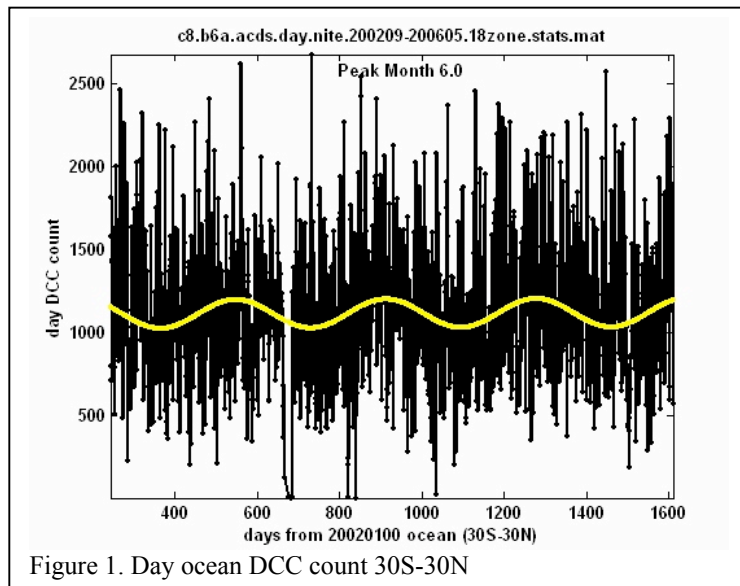


Figure 1. Day ocean DCC count 30S-30N

About 6000 DCC are identified each day, corresponding to about 0.5 % of the AIRS footprints at the 1:30 pm day time and the 1:30 am night time overpasses, land and ocean. The DCC are almost exclusively within 30 degrees of the equator. More detailed analysis reveals zonal differences and differences between the major oceans (Indian, Eastern and Western Pacific, Atlantic).

Figure 1 shows the count of DCC between for tropical day time ocean (± 30 degree latitude). The mean value is 1067, with no significant trend ($+0.3 \pm 1.0$ percent increase

per year in the mean count of 1067 per day). The trend and trend uncertainty are calculated by fitting the daily data to a simple model: $\text{count} = a + b \cdot t + c \cdot \cos(2 \cdot \pi \cdot (t - t_0) / 365.4)$, where b is the trend per day and t_0 is the phase of the annual seasonal modulation. The trend uncertainty is derived from the uncertainty of the slope of the difference between the data and the model fit.

Table 1 shows the day/night trend and the trend uncertainty in the DCC count for four years of AIRS data as percent of the total count for the global tropical oceans, and separately for the Atlantic, E.Pacific, W.Pacific and Indian oceans.

Table 1. Ocean Zone	day trend %/year	night trend %/year
+/-30 degree latitude global oceans	0.3+/-1.0	-2.2+/-0.9
Atlantic	+9.1+/-2.5	+10.3+/-2.6
E.Pacific	-4.6+/-3.1	-6.4+/-2.7
W.Pacific	+1.0+/-1.5	-2.4+/-1.5
Indian	-3.5+/-2.1	-3.7+/-2.0

We define a trend as significant if its absolute value is three time larger than the estimated uncertainty of the trend. Only the Atlantic ocean shows a significant increase in the number of DCC both day and night over the past four years. Further analysis or correlations are beyond the scope of this paper.

DCC are part of the response of the atmosphere to the seasonal variation of the solar input, and as such the DCC count should correlate with the solstice. For global data selected symmetrically around the equator the seasonal variability should be absent, but, as seen in Figure 1, there is a weak seasonal variability due to the asymmetry between the northern and southern distribution of the tropical oceans, which favors the northern oceans.

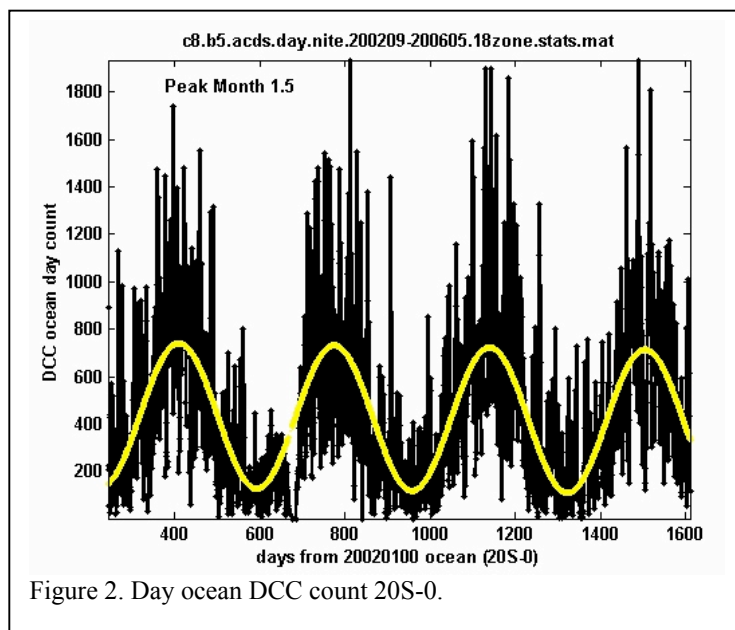


Figure 2 shows the DCC count between 20S and the equator from ascending orbits for each day. As expected, there is a strong seasonal variability in the DCC count for the 0-20S zone, with a peak on the 45th day of each year, corresponding to about 1.8 months after the southern solstice. The lag relative to the peak of the solar input at solstice relates to the thermal inertia of the atmosphere and the mixed layer of the ocean. There is no significant trend in the daily count during four year period (nominally -2.9+/-1.6 percent/year in the mean of about 445 count during the day overpass). It is interesting to note that the DCC count from the night overpasses is consistently larger. For the night overpasses the mean count is 621,

40% more than during the day time overpasses.

Table 2. shows the phase relative to the solstice for four latitude zones and the night overpasses in units of fractional months. Also shown in Table 1 are the phase of the peak of the sea surface temperature (SST) and the phase of the total precipitable water column (TW), all obtained from the AIRS data.

Table 2. Ocean zone (night)	DCC phase	SST phase	Total Precip.water phase
20-40N	2.1	2.7	2.5
0-20N	1.6	1.0	1.6
20S-0	1.8	2.5	2.5
40S-20S	2.4	2.8	2.5

Table 2 reveals interesting differences between the phase of the DCC peak, the peak of the SST and the peak of the TW relative to the solstice. On average the peak of the DCC count lags the solstice by 2

months, but the lag is larger at higher latitudes. The SST and TW should be totally correlated over ocean, and on average they are. Typically the peak of the SST and the TW lag the solstices by 2.25 months, so the DCC are already declining when the SST is still increasing. There is also a curious difference in the lag of the 0-20N zone. These observations are clearly of interest to climate models, but further analysis of the phase, thermal inertia and zonal differences is required, which is beyond the scope of this paper.

2.2. Spectral patterns

The AIRS hyperspectral data provides information about the composition of the tops of the DCC.

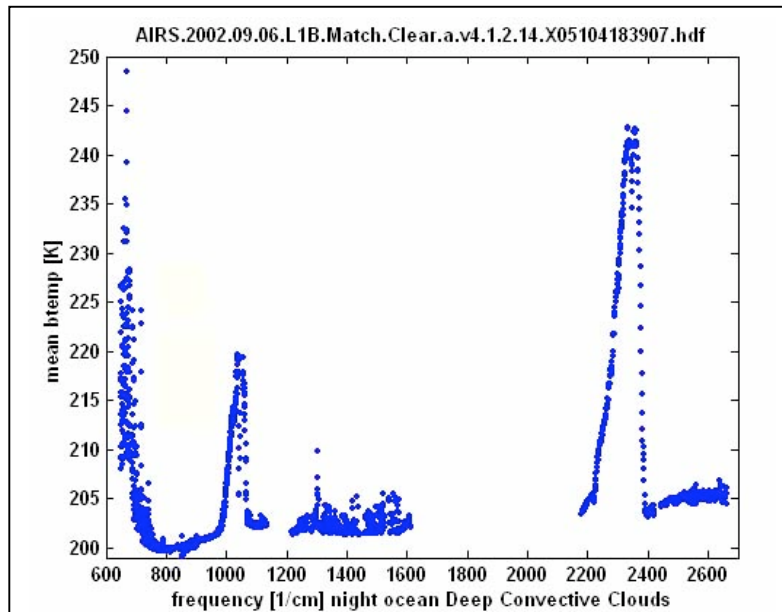


Figure 3. Average tropical ocean night spectrum of a DCC.

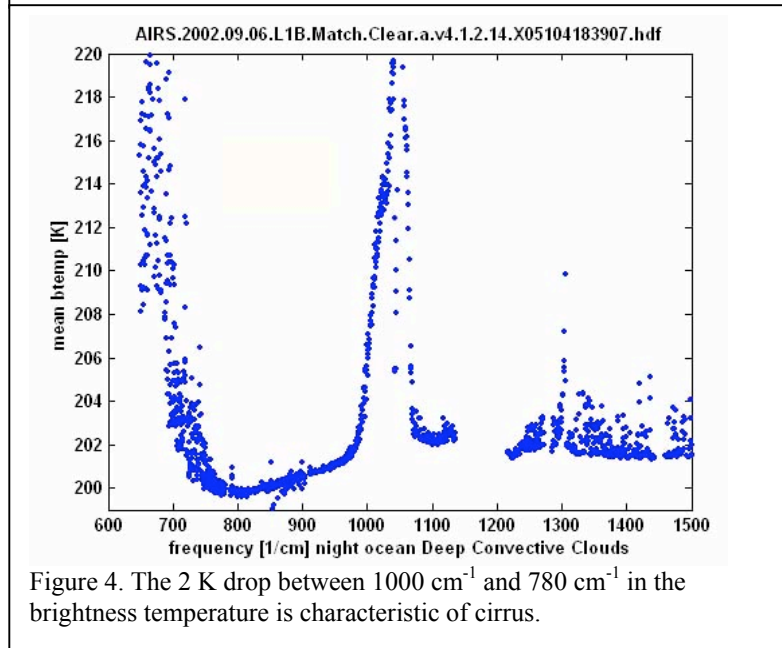


Figure 4. The 2 K drop between 1000 cm^{-1} and 780 cm^{-1} in the brightness temperature is characteristic of cirrus.

Figure 3 shows the mean brightness temperature of all DCC between ± 30 degree from all night ocean data from one day, 6 September 2002. This spectrum, which is very typical, shows that DCC do not look at all like blackbodies. The most prominent features in the spectrum are due to the emission from CO_2 and ozone in the stratosphere above and warmer than the top of the DCC. The CO_2 lines are between 2200 and 2400 cm^{-1} and at frequencies lower than 750 cm^{-1} . The ozone lines are between 1000 and 1050 cm^{-1} . The spectral features due to stratospheric water are relatively minor. Note that the definition of the DCC is based on the brightness temperature threshold of 210K at 1231 cm^{-1} , but that the average there is 203 K, and the short-wave window channels have a brightness temperature of about 205 K.

Figure 4 zooms in on the 600-1500 cm^{-1} region of the spectrum. The gap between about 1150 cm^{-1} and 1210 cm^{-1} is due to a gap in the AIRS spectral coverage. The 8 K peak near 1300 cm^{-1} is due to stratospheric methane. If we focus on the lower envelope of the spectrum we see a relatively smoothly varying spectral signature due to the effective emissivity of the cloud top. The lower envelope in the 1200 cm^{-1} to 1500 cm^{-1}

region of the spectrum is at 202 K, the temperature then rises by 0.5K in the 1100 cm^{-1} region, then drops between 1000 cm^{-1} and 780 cm^{-1} to a minimum at 200 K. The major features of this spectrum can be reproduced by assuming that the DCC is covered by a layer of cirrus.

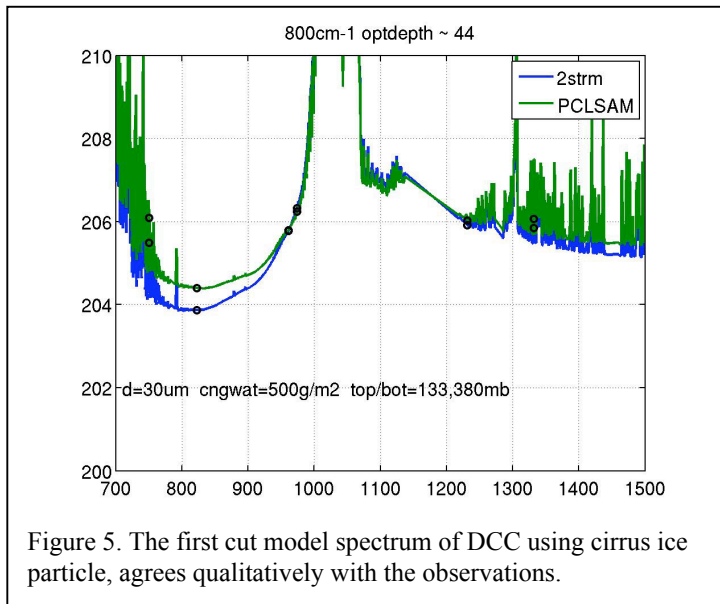


Figure 5. The first cut model spectrum of DCC using cirrus ice particle, agrees qualitatively with the observations.

Figure 5 shows a first cut model spectrum of the DCC assuming a tropical climatology atmosphere with the nominal vertical distribution of ozone and methane. The model assumes that the top of the DCC has a layer of ice (cirrus) particles between 133 and 380 mb. The mean particle diameter is 30 micron diameter ice (cirrus) particles, with a column amount $cngwat=500g/m^2$. Two different models, 2strm and PCLSAM produce very similar results. No attempt was made to fine tune the model, e.g. the brightness temperature minimum is at 204 K, not the observed 200 K. Analysis of other days show that Figure 5 is typical, but there is a day/night land/ocean pattern in the details. The

magnitude of the temperature drop between 1000 cm^{-1} and 780 cm^{-1} is typically in the 1 K to 2.5 K range. Details are beyond the scope of this paper.

3. Discussion

The observations of DCC with AIRS show the potential for the derivation of a number of climate model parameters and trends. Data for the trend analysis can be started with AIRS, some can be extended into the past using the HIRS sounders on the NOAA operational polar orbiting satellites, and all can be extended by the next generation of hyperspectral infrared sounders on the NOAA operational polar orbiting sounders, starting in 2006 with the launch of IASI and in 2010 with the CRIS on the NPP. The potential climate related questions which can be answered can be divided into counting statistics and spectral characterization statistics.

Counting statistics:

The availability of 6000 events per day allows for very accurate trend analysis, but only if the radiometric calibration is extremely stable. The precise absolute calibration and calibration stability at 210K stress the state of art of infrared radiometry. If the threshold used in the DCC count were to drift by 100 mK from 210 K to 209.9 K due to an undetected drift in the calibration, the DCC count would typically decrease by 1.2%. The correct interpretation of the relationship between the real DCC count and the apparent decrease in the DCC count would be very difficult. Fortunately, the calibration stability of AIRS has been verified with an upper limit of 16 mK/year level using the first three years of AIRS data (Aumann et al. 2006). A 16 mK/year trend would create a false trend in the DCC count of 0.2 percent per year. The first cut at the trend analysis shows that the DCC count has been relatively stable globally, but the day and night count for the tropical Atlantic ocean has increased by 10% per year during the past four years. With only four years of data from AIRS it is difficult to tell how much of this trend is due to inter-annual variability. Other questions which can be answered with AIRS data are: Is there a N/S dependence? Is the number of DCC at latitudes above 20N or 30N correlated with the number of named hurricanes? These correlations require long data sets to dampen out inter-annual variability. The nominal lifetime of AIRS and the EOS Aqua spacecraft is seven years, but current estimates based on the aging of components and the supply of attitude control gas lead to the expectation of data through 2014, i.e. a 12 year data set.

The AIRS data set can potentially be extended in the past with HIRS data and into the future with IASI and CRIS data. However, the extension of DCC trends from AIRS to HIRS, IASI or CRIS will be complicated by several factors:

- 1) We have already discussed the extreme calibration stability requirement, there is also the issue of absolute calibration. The absolute calibration at 210 K between different sensors, e.g. AIRS vers. MODIS Aqua, or AIRS versus HIRS/2 on NOAA/16 can be verified at about the 200 mK level (Broberg et al. 2006). For most objectives this is good enough, but not for the DCC count, where a 200 mK calibration shift would produce an artificial shift in the DCC count by 2%.
- 2) HIRS/2 has 20 km footprints, compared to the AIRS 13 km, the HIRS/4 have 10 km footprints. CRIS and IASI have nominal footprint sizes close to AIRS, but AIRS is scanning, producing a footprint smear, while CRIS and IASI are staring.
- 3) The DCC are not blackbodies. This is an issue only for the HIRS relative broad 10 micron window channels. Based on Figure 4 a 209K threshold for HIRS in the 11 micron thermal IR channel is only approximately equivalent to a 210 K threshold in the AIRS 1231 cm^{-1} channel.
- 4) The fact that the night count of DCC by AIRS is consistently larger than the day count indicates that there are significant diurnal effects, which have to be accounted for when extending trends to different orbits. The orbits of the NOAA polar orbiters were not maintained at a constant ascending node, causing a convolution of any count with diurnal variability. The IASI is a 10 AM ascending node orbit, while CRIS will be in a 2 PM descending node polar.

Spectral characteristics:

The first cut fit to the mean tropical ocean spectra suggest cirrus ice with 30 micron diameter mean particle size. Trapping of upwelling radiation by cirrus in cloud-free areas is an important contributor to the greenhouse effect. Is the detrainment of the cirrus from the DCC the main source of the cirrus in the cloud-free spectra? This would manifest itself as a correlation between the amount and/or the character of the cirrus seen in “cloud-free” AIRS spectra and the number of DCC. Further analysis is required. Is there a trend or are there seasonal ocean or zonal dependent changes in the character of the cirrus layer at the top of the DCC? If AIRS data detect a pattern, then a continuation of the evaluation with IASI and/or CRIS is possible, since the spectra analysis is less sensitive to absolute calibration issues.

All of these questions point into a potentially very fruitful direction of future research related to DCC and climate research.

4. Summary

Deep Convective Clouds, also known as large thunderstorms, can be identified in the AIRS data as areas where the brightness temperature of the 1231 cm^{-1} atmospheric window channel in non-polar areas is less than 210 K. Each day about 6000 such objects are identified, almost exclusively within 30 degrees of the equator. The global distribution of DCC over land and ocean and their physical properties may hold answers related to global warming and climate change. We discuss DCC as seen in the AIRS data in terms of the global day/night ocean zonal distribution, global and major ocean trends, the phase of the peak count relative to the solstice and their spectral properties. The most prominent features in brightness temperature spectra of DCC are due to stratospheric CO_2 , Ozone and Methane. The characteristic 1 to 2.5 K drop between 1000 and 750 cm^{-1} , equivalent to a 2-4 % drop in emissivity, is attributed to cirrus (ice) particles on top of the cloud. The patterns seen in the AIRS data over the past four years can be extended into the past and the future using the operational sounders in polar orbit.

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